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Study on mechanical property and electromagnetic emission during the fracture process of combined coal-rock

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Abstract

The mechanical characteristics and electromagnetic emission rules during the uniaxial compression of the combined coal-rock were investigated in laboratory and its mechanical property was analyzed; the relation between mechanical characteristics and electromagnetic emission of the combined coal-rock was discussed. The results show that the combined coal-rock strength under the uniaxial compression is obviously different from that of single coal or rock and the fracture process of the combined coal-rock is gradual, accompanied by electromagnetic emission. This research has an important significance to further understanding of the mechanism and forecasting method of coal or rock dynamical disasters in theory and practice.

Keywords: combined coal-rock; electromagnetic emission; mechanical property

1. Introduction

Electromagnetic emission of coal-rock is a process and phenomenon in which coal-rock body radiates electromagnetic energy in its fracture under loading deformation. The laboratory has conducted large quantities of study as to the strength change characteristics in the fracture process of single coal-rock and its electromagnetic emission rules [1,2], and also applied theory on the site[3]. In the field of coal mine, however, coal-rock bodies are mostly composite coal-rock layers, and a majority of them are located under complicated stress state, such as triaxiality, creepage and stress relaxation. Coal-rock dynamic disasters, like coal and gas outburst and pressure bump, just occurs in the process of sudden changes of coal bed under such complicated stress field including ceiling and floor confining pressure. Therefore, study on the electromagnetic emission rules of composite coal-rock layer has an important significance to further understand the mechanism and forecasting method of coal or rock dynamical disasters in theory and practice.

2. Analysis of mechanical property of combined coal-rock under load

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2.1. Analysis of stress of combined coal-rock sample under uniaxial compression

Combined coal-rock sample consists of sandstone, coal sample and mudstone, as shown in Fig.1. The following assumptions are made as for its mechanical property: (1) it is considered that there exists cohesive force on the interface between rock and coal sample. After combined coal-rock sample is deformed under load, no relative slippage occurs on the interface between the adjacent rock and coal sample. (2) Among combined coal-rock sample, the elastic modulus, Poisson ratio, shear elastic modulus and extent of ultimate destruction of each rock vary. (3) Neglecting the width of adhesive substances on the interface between rock and coal sample, it is thought that the components of combined coal-rock sample are directly bound together.

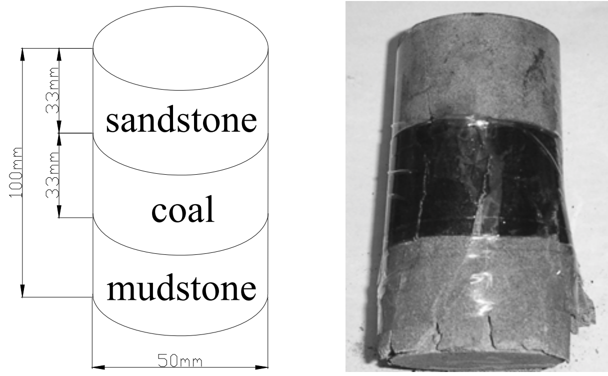

Fig. 1. Schematic diagram of combined coal-rock sample

Known elastic modulus of sandstone, coal sample and mudstone is E_S, E_M and E_N, respectively, and their Poisson ratio is μ_S, μ_M and μ_N, respectively

According to rock mechanics-related theory, The layered coal-rock sample being acted by axial compressive stress σ_1, the deformation of S, M and N different rocks at horizontal direction (i.e., direction 2 and 3) has a relation: $\varepsilon_{2S}=\varepsilon_{3S}<\varepsilon_{2N}=\varepsilon_{3N}<\varepsilon_{2M}=\varepsilon_{3M}$. On S and M rock interface and on M and N rock interface, due to mutual restraint of lateral strain, adhesive restrain stress will be produced among the rocks on both sides.

On S and M rock interface, a shear elastic modulus 3D unit body is taken, as shown in Fig. 2(1). It is known that, due to adhesive restraint relation, S rock will produce lateral tensile stress, and M rock will produce lateral compressive stress, and no shear stress will arise due to adhesive restrain relation on the rock interface.

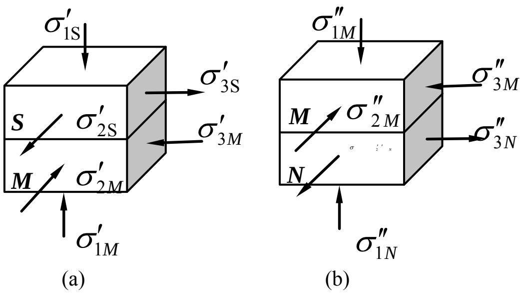

Fig. 2. Shear elastic modulus 3D unit body on *S* and *M* interface and on *M* and *N* interface

Through mechanics analysis of shear elastic modulus 3D unit body, such as continuation conditions of deformation and static equilibrium conditions, the following stress and strain relation can be obtained:

$$\begin{cases} \varepsilon'_{2S} = \varepsilon'_{2M} = \varepsilon'_2 \\ \varepsilon'_{3S} = \varepsilon'_{3M} = \varepsilon'_3 \\ \varepsilon'_2 = \varepsilon'_3 \end{cases} \tag{1}$$

$$\begin{cases} \sigma'_{1S} = \sigma'_{1M} = \sigma'_1 \\ \sigma'_{2S} = \sigma'_{2M} = \sigma'_2 \\ \sigma'_{3S} = \sigma'_{3M} = \sigma'_3 \\ \sigma'_2 = \sigma'_3 \end{cases} \tag{2}$$

where, ε'_{2S}, ε'_{2M}, ε'_{3S} and ε'_{3M} are the strains of *S* and *M* part at directions 2 and 3, respectively; σ'_{2S}, σ'_{2M}, σ'_{3S} and σ'_{3M} are the restrain stresses of *S* and *M* part at directions 2 and 3, respectively; and σ'_{1S} and σ'_{1M} represent the positive pressure of *S* and *M* at direction 1.

According to generalized Hooke Law, the strains of S and M at directions 2 and 3 are:

$$\begin{cases} \varepsilon'_{2S} = \dfrac{1}{E_S}[-\sigma'_{2S} - \mu_S(\sigma'_{1S} - \sigma'_{3S})] \\ \varepsilon'_{2M} = \dfrac{1}{E_M}[\sigma'_{2M} - \mu_M(\sigma'_{1M} - \sigma'_{3M})] \end{cases} \tag{3}$$

$$\begin{cases} \varepsilon'_{3S} = \dfrac{1}{E_S}[-\sigma'_{3S} - \mu_S(\sigma'_{1S} - \sigma'_{2S})] \\ \varepsilon'_{3M} = \dfrac{1}{E_M}[\sigma'_{3M} - \mu_M(\sigma'_{1M} - \sigma'_{2M})] \end{cases} \tag{4}$$

From Formula (1), (2), (3) and (4), the stresses on S and M interface are deduced:

$$\begin{cases} \sigma'_{2S} = \sigma'_{2M} = \sigma'_{3S} = \sigma'_{3M} = \sigma'_2 = \sigma'_3 = K_{SM}\sigma_1 \\ \sigma'_{1S} = \sigma'_{1M} = \sigma_1 \end{cases} \tag{5}$$

where, $K_{SM} = \dfrac{E_S\mu_M - E_M\mu_S}{E_S(1-\mu_M) + E_M(1-\mu_S)}$.

Likewise, the stress relation on M and N interface is deduced:

$$\begin{cases} \sigma''_{2M} = \sigma''_{2N} = \sigma''_{3M} = \sigma''_{3N} = \sigma''_2 = \sigma''_3 = K_{MN}\sigma_1 \\ \sigma''_{1M} = \sigma''_{1N} = \sigma_1 \end{cases} \tag{6}$$

where, $K_{MN} = \dfrac{E_N\mu_M - E_M\mu_N}{E_N(1-\mu_M) + E_M(1-\mu_N)}$, as shown in Fig.2(2).

It can be seen from Formula (5) and (6), due to adhesive restrain relation on the rock interface, *S* rock changes into 3-way tensile stress state, *M* rock into 3-way compressive stress state, and *N* rock into 3-way tensile stress state. This indicates that the stress state on *S*, *M* and *N* rock interface changes.

Hence, because of not being imposed on adhesive restraint stress or under less stress, *S*, *M* and *N* rock that are located outside the area of each rock interface are considered to still be under one-way compressive stress state acted by σ_1.

2.2. Analysis of uniaxial strength conditions of combined coal-rock

According to Mohr's strength theory in rock mechanics, if the uniaxial compressive strength of each rock in horizontal layered rock mass is known, then Mohr's strength condition expressions of *S*, *M* and *N* rock are below:

$$\sigma_{1Sj} = \frac{1+\sin\varphi_S}{1-\sin\varphi_S}\sigma_{3j} + R_{cS} \tag{7}$$

$$\sigma_{1Mj} = \frac{1+\sin\varphi_M}{1-\sin\varphi_M}\sigma_{3j} + R_{cM} \tag{8}$$

$$\sigma_{1Nj} = \frac{1+\sin\varphi_N}{1-\sin\varphi_N}\sigma_{3j} + R_{cN} \tag{9}$$

where, σ_{1j} and σ_{3j} denote two ultimate main stresses of rock under ultimate stress equilibrium state, respectively; R_{cS}, R_{cM} and R_{cN} denote uniaxial compressive strength of *S*, *M* and *N* rock, respectively; and φ_S, φ_M and φ_N denote internal friction angle of *S*, *M* and *N* rock, respectively.

On *S* and *M* interface, if *S* and *M* are under ultimate stress equilibrium state, respectively; then from Formula (5), the ultimate stress strength of *S* and *M* rock is deduced:

$$\begin{cases} \sigma_{1Sj} = \sigma'_{1S} \\ \sigma_{3Sj} = \sigma'_{3S} = K_{MN}\sigma'_{1S} < 0 \end{cases} \tag{10}$$

$$\begin{cases} \sigma_{1Mj} = \sigma'_{1M} \\ \sigma_{3Mj} = \sigma'_{3M} = K_{MN}\sigma'_{1M} > 0 \end{cases} \tag{11}$$

From Formula (7), (10), (8) and (11), the axial ultimate compressive strength of *S* and *M* rock can be written as:

$$\sigma'_{1Sj} = \frac{R_{cS}}{1+\alpha_S K_{SM}} \tag{12}$$

$$\sigma'_{1Mj} = \frac{R_{cM}}{1-\alpha_M K_{SM}} \tag{13}$$

On *M* and *N* interface, if *M* and *N* are under ultimate stress equilibrium state, likewise, computation can deduce the axial ultimate compressive strength of *S* and *M* rock:

$$\sigma''_{1Mj} = \frac{R_{cM}}{1-\alpha_N K_{MN}} \tag{14}$$

$$\sigma''_{1Nj} = \frac{R_{cN}}{1+\alpha_N K_{MN}} \tag{15}$$

From Formula (12)-(15), the following strength relation is deduced:

$$\begin{cases} \sigma'_{1Sj} < R_{cS} \\ \sigma'_{1Mj} > R_{cM} \end{cases} \tag{16}$$

$$\begin{cases} \sigma''_{1Mj} > R_{cM} \\ \sigma''_{1Nj} < R_{cN} \end{cases} \tag{17}$$

Formula (16) suggests that, on the interface of *S* and *M* rock, the axial ultimate compressive strength of *S* rock is somewhat decreased, its value is smaller than the uniaxial compressive strength R_{cS} of *S* single rock; the axial ultimate compressive strength of *M* rock is somewhat increased; and its value is larger than the uniaxial compressive strength R_{cM} of *M* single rock.

Hence, the strength of *S* rock is decreased, while that of *M* rock is increased. Formula (17) shows that, on the interface of *M* and *N* rock, the axial ultimate compressive strength of *M* rock is larger than the uniaxial compressive strength R_{cM} of *M* single rock; the axial ultimate compressive strength of *N* rock is larger than the uniaxial compressive strength R_{cN} of *N* single rock. Hence, here, the strength of *M* rock is increased, while that of *N* rock is decreased.

S, *M* and *N* rock that are located outside the area of rock interface are still under one-way compressive stress state. In these areas, *S*, *M* and *N* rock are still under uniaxial compressive strength, and their values are R_{cS}, R_{cM} and R_{cN}, respectively.

3. Results and analysis of experiment of combined coal-rock under load

3.1. Theoretical value of axial ultimate compressive strength of combined coal-rock

The combined coal-rock sample used in the experiment consists of adhered ceiling sandstone, coal bed and floor mudstone, and the binding agent is the mixture of epoxy resin and ethanediamine. Its shape and size are shown in Fig. 1. The mechanical parameters of each sandstone, coal and mudstone are shown in Table 1. According to the above analysis, the theoretical value of axial ultimate compressive strength of each rock on different rock interface can be figured out, as shown in Table 2.

Table 1. The mechanical parameters of each single rock in combined coal-rock sample

	Uniaxial compressive strength (MPa)	Elastic modulus (kMPa)	Poisson ratio	Internal friction angle (º)
Sandstone	130.94	95.24	0.24	32.58
Coal	6.10	13.55	0.25	26.62
Mudstone	95.00	68.56	0.25	30.00

Table 2. Axial ultimate compressive strength of each rock on the interface area

	K value	Axial ultimate compressive strength on interface area (kMPa)
Sandstone-coal bed	0.26	σ'_{1Sj} =70.23, σ'_{1Mj} =19.09
Coal bed-mudstone	0.23	σ''_{1Mj} =56.23, σ''_{1Nj} =15.46

3.2. Experimental results and analysis

The loading system used in the uniaxial compression experiment for combined coal-rock sample is Japanese EHF-UG500KN fully digital hydraulic experiment system. Electromagnetic emission signals are acquisitioned by sound-electric data whole waveform acquisition system developed by ourselves.

By observation of the phenomena found in the experiment (as shown in Fig. 3.), the fracture of combined coal-rock sample is gradual, namely, as the load increases, the coal with lower strength is fractured at first, the first obvious unloading appears; later, as the load further increases and the coal is gradually compressed firmly, the stress in mudstone and sandstone gradually increases and reaches to a certain extent, the mudstone with the second lower strength is fractured, and the second significant unloading then occurs. Subsequently, due to limit by maximum displacement, the presser automatically ceases to add load and the experiment was ended. It can be seen from the figure that, the load value in fracture of combined coal-rock is about 18.85MPa, far larger than the strength value of single modestly hard coal sample that is 6.10 MPa. And the strength value in fracture of mudstone is 61.15MPa, smaller than the strength value of single mudstone sample that is 95.15MPa.

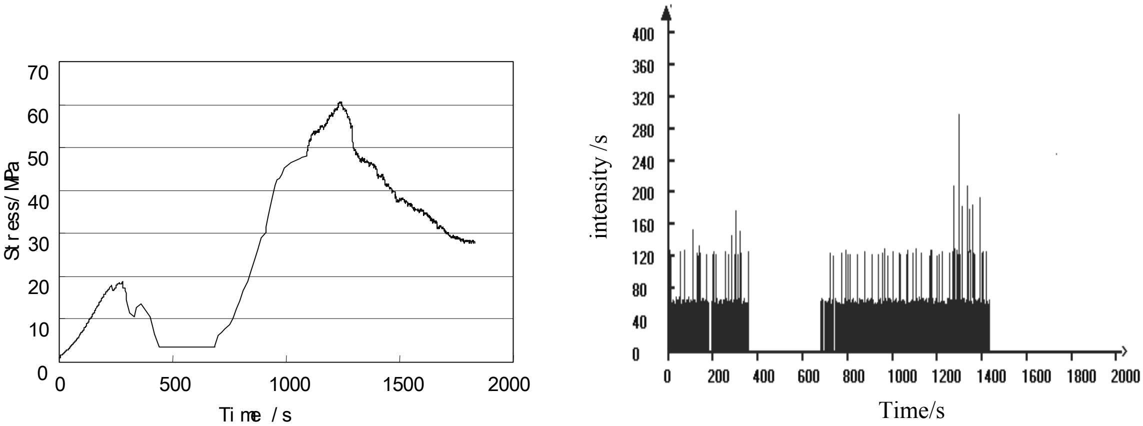

Fig.3. Correspondence between uniaxial compression fracture stress of combined coal-rock and electromagnetic emission

It can be seen from Formula (16) and (17), on the interface between upper and middle coal bed and on the interface between middle coal bed and bottom mudstone, due to lateral restraint stress relation, middle coal bed *M* changes from single compression stress state into 3-way compression stress state. After superposition, the axial ultimate compression strength σ_{1Mj} of the coal bed of the combined coal-rock body is far larger than the uniaxial compressive strength of single coal sample R_{cM}, that is, there appears strength change: 18.85MPa > 6.10 MPa. Owing to extension of internal cracks of each layer, a large quantity of electromagnetic emission signals are generated, and the first electromagnetic emission signal peak comes into being. As the load is continually increased, the fractured portion of middle coal bed is gradually compressed firmly, at which time because no new fracture and internal friction take place, no electromagnetic emission signals of fracture are generated. As the load is continuously increased, the coal is gradually compressed firmly, the middle portion continually realizes transfer of force. It can be seen from Formula (17) that, on the interface between middle coal bed and bottom mudstone, bottom mudstone N changes from single compression stress state into 3-way tensile stress state, making the axial ultimate compression strength of the mudstone of the combined coal-rock body σ''_{1Nj} smaller than the uniaxial compressive strength of single mudstone R_{cM}. By observation in the experiment, the fracture strength in the second fracture (fracture of bottom mudstone) is 61.15MPa, which is smaller than the strength of single mudstone sample that is 95.15MPa, and approximates to the theoretical analysis result, that is 56.23 MPa. At this time, due to further extension of internal crack of each layer and friction squeezing of broken coal particles, electromagnetic emission signals form the second peak value, and the volume of the signals is also richer than the first time.

4. Conclusions

Uniaxial loading experiment results of combined coal-rock sample and theoretical analysis suggest that:

1) The strength of layered combined coal-rock body is evidently different from that of each single rock, mainly attributable to lateral strain restraint effect on the rock interface. The theoretical analysis computation result is in good agreement with the experiment. one

2) When combined coal-rock body is acted under uniaxial compression stress, the fracture of the stone insider the rock body is a gradual process.

3) In the deformation fracture process of combined coal-rock under the load of uniaxial compression, electromagnetic emission signals are always generated. In both fractional and simultaneous fracture process of coal and mudstone, electromagnetic emission enhancement phenomenon occurs; when coal-rock fractures, the load reaches the maximum value, and electromagnetic emission signals are also the strongest.

4) The results of experimental research provide theoretical basis for field application and necessary parameters base to the development of in-situ electromagnetic emission monitoring system, and are of important significance to analysis and forecasting of coal-rock dynamic disaster.

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